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FOR

MEMS DEVICE FOR AN ADAPTIVE OPTICS MIRROR

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CROSS-REFERENCE TO RELATED APPLICATION

The subject matter of this application is related to that of U.S. Patent Application No. 10/772,847, also identified by attorney docket reference Greywall 31, filed February 5, 2004, which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to adaptive optics and, more specifically, to micro-electromechanical systems (MEMS) for implementing adaptive optics.

Description of the Related Art

Adaptive optics is a field of optics dedicated to the improvement of optical signals using information about signal distortions introduced by the environment in which the optical signals propagate. An excellent introductory text on the subject is given in "Principles of Adaptive Optics" by R. K. Tyson, Academic Press, San Diego, 1991, the teachings of which are incorporated herein by reference.

A representative example of an adaptive optical element is a deformable mirror driven by a wavefront sensor and configured to compensate for atmospheric distortions that affect telescope images. Small naturally occurring variations in temperature (~ 1°C) in the atmosphere cause random turbulent motion of the air and give rise to changes in the atmospheric density and, hence, to the index of refraction. The cumulative effect of these changes along the beam propagation path may lead to beam wandering, spreading, and intensity fluctuations, each of which degrades image quality. The wavefront sensor is a device that measures the distortions introduced in the atmosphere and generates feedback for the deformable mirror. Based on the feedback, the mirror is deformed such that the beam distortions are significantly reduced, thus improving the image quality.

One frequently used type of deformable mirror is a segmented mirror, in which each segment (pixel) can individually be translated and/or rotated. For many applications, a segmented mirror is required to have: (1) for each segment, translation/rotation magnitudes on the order of 1 μm/10 degrees, respectively, and (2) for the mirror as a whole, a fill factor of at least 98%. However, for many prior-art designs, these requirements are in direct

conflict with each other and therefore difficult or even impossible to meet. For example, the high fill-factor requirement suggests a solution, in which mirror support elements and motion actuators are placed beneath (hidden under) the mirror. One result of this placement is that each segment typically rotates about an axis lying below the mirror surface and therefore is subjected to a lateral displacement within the mirror plane during rotation. To prevent physical interference with the neighboring mirror segments caused by this displacement, a relatively large spacing between the segments is required. The latter, however, significantly reduces the fill factor.

SUMMARY OF THE INVENTION

Problems in the prior art are addressed, in accordance with the principles of the present invention, by a MEMS device having a movable mirror pixel supported on a substrate and coupled to a motion actuator located between the mirror pixel and the substrate so as to enable rotation of the mirror pixel about an axis lying within the mirror plane.

In one embodiment of the invention, the motion actuator has a movable electrode, on which the mirror pixel is mounted. The movable electrode is supported on the substrate by a pair of upright springs, each having two parallel segments joined at one end of the spring and disjoint at the other end. One disjoint segment end is coupled to the substrate, while the other disjoint segment end is coupled to the movable electrode. The end of the upright spring corresponding to the joined segment ends points away from the substrate such that (i) the spring body protrudes through a narrow slot in the mirror pixel and (ii) the mirror plane lies at about the mid-point of the upright spring. Advantageously, a mirror pixel implemented in accordance with an embodiment of the invention has a relatively small lateral displacement during rotation while the mirror support structure takes up a relatively small surface area within the mirror plane. This enables implementation of a segmented mirror with tightly spaced mirror pixels providing a fill factor higher than about 98%.

In another embodiment of the invention, a MEMS device has an upright spring supported on a substrate. The upright spring has two segments joined at one end of the spring and disjoint at another end of the spring. The upright spring is positioned with respect to the substrate such that the joined segment ends are at a greater distance from the substrate than the disjoint segment ends. One disjoint segment end is coupled to the

substrate and the other disjoint segment end is adapted to move with respect to the first one via a scissor-type motion.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a three-dimensional perspective view of a MEMS device according to one embodiment of the invention;

Figs. 2A-C show a MEMS device according to another embodiment of the invention;

Fig. 3 shows a cross-sectional view of a MEMS device according to yet another embodiment of the invention;

Fig. 4 shows a three-dimensional perspective view of a MEMS device according to yet another embodiment of the invention; and

Figs. 5A-F illustrate representative fabrication steps of the device shown in Fig. 2 according to one embodiment of the invention.

DETAILED DESCRIPTION

Fig. 1 shows a three-dimensional perspective view of an exemplary MEMS device **100** arranged in accordance with the principles of the invention, which may be used to implement a pixel of an adaptive optics mirror. Device **100** has a movable plate **102** and connected to a motion actuator **110**. Plate **102** is supported by a pair of torsion rods **106a-b**, each connected between the plate and one of posts **104a-b** attached to a substrate **170**. Rods **106a-b** define an axis of rotation for plate **102** shown by the dashed line and labeled AB in Fig. 1.

Actuator **110** is a fringe-field actuator made up of two lateral electrodes **112a-b** and an intermediate electrode **114**. Lateral electrodes **112a-b** are attached to substrate **170** and, as such, are stationary. In contrast, intermediate electrode **114** is attached to plate **102** by a link rod **116** and, as such, is movable, together with the plate, with respect to substrate **170**. When intermediate electrode **114** is moved toward one of lateral electrodes **112**, link rod **116** transfers motion of the intermediate electrode to plate **102**, thereby rotating the plate about axis AB.

Each lateral electrode **112** is electrically isolated from substrate **170** by an insulation layer **180** and can be electrically biased with respect to the substrate. In contrast, intermediate electrode **114** is in electrical contact with substrate **170** via link rod

116, plate **102**, torsion rods **106**, and posts **104**. Therefore, electrodes **112** and **114** can be electrically biased with respect to each other to impart motion to plate **102**. For example, when lateral electrode **112a** is biased with respect to intermediate electrode **114** while lateral electrode **112b** is not biased, the intermediate electrode is pulled toward the biased electrode, which rotates plate **102** in the corresponding direction. Plate **102** comes to rest, when spring deformation forces of torsion rods **106** balance the electrostatic attraction force between the electrodes. When the bias is removed, the spring forces return plate **102** and intermediate electrode **114** into the initial position. Similarly, when lateral electrode **112b** is biased with respect to intermediate electrode **114** while lateral electrode **112a** is not biased, plate **102** rotates in the opposite direction.

Figs. 2A-C show another embodiment of the invention. More specifically, Fig. 2A shows a three-dimensional perspective view of a MEMS device **200**; Fig. 2B shows a three-dimensional perspective view of a spring **206** utilized in device **200**; and Fig. 2C is a side view of device **200** illustrating possible plate rotation.

Referring to Fig. 2A, device **200** is similar to device **100** of Fig. 1 and may similarly be used to implement a pixel of an adaptive optics mirror. Device **200** has a movable plate **202** supported on a substrate **270** and connected to a motion actuator **210** that is similar to actuator **110** of device **100**. However, instead of torsion rods **106a-b** of device **100**, device **200** employs upright springs **206a-b**, one of which is shown in more detail in Fig. 2B. Referring now to both Figs. 2A and 2B, each upright spring **206** has two feet **226a-b**, one of which is connected to a corresponding one of support posts **204a-b** and the other is connected to an intermediate electrode **214** of actuator **210**. Each upright spring **206** has two spring segments **228a-b** that protrude through a slot (opening) **208** in plate **202** as shown in Fig. 2C without attaching to the plate. Spring segments **228a-b** are joined at the top of upright spring **206** by a bridge **230**. In a preferred implementation, the width and thickness (W_{seg} and t_{seg}) of segments **228** are such that upright spring **206** resists compression along the direction orthogonal to the plane of substrate **270** (i.e., has high longitudinal stiffness) while it permits a relatively easy spring deformation of the "scissor" type shown in Fig. 2C.

Referring now to Fig. 2C, when intermediate electrode **214** is displaced from its unbiased position shown in Fig. 2A, one foot of upright spring **206** moves together with the intermediate electrode while the other foot, being rigidly attached to post **204**, remains stationary. It can be shown that, due to the longitudinal stiffness of upright

spring **206**, motion of any structure attached to the movable foot of the spring is very closely approximated by a simple rotation about an axis passing through the mid-point (i.e., at half-length) of the spring, which point is labeled P in Fig. 2C. Therefore, when link rod **216** has a length L_r equal to about half the length of upright spring **206**, plate **202** rotates about an axis lying within the plane of plate **202** similar to that for plate **102** in device **100** (Fig. 1). In certain implementations of device **200**, the surface area within the plane of plate **202** taken up by slots **208** can be made significantly smaller than the corresponding area within the plane of plate **102** taken up by posts **104** and torsion rods **106** in device **100**. This increases the fill factor of device **200** compared to that of device **100**.

Fig. 3 shows a cross-sectional view of a MEMS device **300** according to yet another embodiment of the invention. Device **300** is similar to device **200** (Fig. 2) with similar structural elements of the two devices marked with labels having the same last two digits. However, one difference between devices **300** and **200** is that, instead of intermediate electrode **214**, device **300** has a cradle structure **334**. Similar to electrode **214** (Fig. 2), cradle structure **334** can move as a whole, when upright springs **306a-b** are deformed, thereby enabling rotation of plate **302** with respect to substrate **370**. But in addition to rotation with respect to substrate **370**, cradle structure **334** enables piston motion of plate **302** along axis Z with respect to the cradle structure.

Cradle structure **334** has a movable plate **332**, on which plate **302** is mounted using link rod **316**. Plate **332** is suspended above a cradle base **338** with a pair of serpentine springs **316** that allow for out-of-plane displacements of plate **332**. An actuating electrode **342** attached to cradle base **338** beneath plate **332** forms, together with that plate, a parallel plate actuator that can be used to translate plate **302**. For example, when electrode **342** is biased with respect to plate **332**, it generates an attractive electrostatic force, which pulls plate **332** toward the electrode, thereby translating plate **302** with respect to cradle structure **334**. When the bias is removed, springs **336** return plates **332** and **302** into their initial positions.

Fig. 4 shows a three-dimensional perspective view of a MEMS device **400** according to yet another embodiment of the invention. Similar to device **200** of Fig. 2, device **400** implements rotation of a movable plate about an axis lying within the plane of that plate. However, in contrast to device **200**, where the movable plate rotates about a

single axis, the movable plate in device **400** can rotate about two different axes, thereby providing a capability for tilting the plate in any desired direction.

Device **400** has a movable plate **402** supported on a substrate **470** and connected to a motion actuator **410**. Plate **402** is mounted using a link rod **416** on a gimbal structure **450** having an outer ring **452** and an inner disk **454**. Outer ring **452** is supported by a pair of upright springs **406a-b**, each attached between the outer ring and one of posts **404a-b** attached to substrate **470**. Inner disk **454** is supported by another pair of upright springs **406c-d**, each attached between the inner disk and outer ring **452**. Each of upright springs **406a-d** is similar to upright spring **206** shown in Fig. 2B and protrudes through a corresponding slot **408** in plate **402**. In a preferred implementation, the length of link rod **416** is about half the length of spring **406**, which puts the axes of rotation defined by springs **406a-b** (axis AB in Fig. 4) and springs **406c-d** (axis CD in Fig. 4) within the plane of plate **402**. Although, in the embodiment of Fig. 4, axes AB and CD are mutually orthogonal, other axis orientations may also be used.

Actuator **410** is a fringe-field actuator comprising three lateral electrodes **412a-c** and an intermediate electrode **414**. Each lateral electrode **412** is similar to, e.g., lateral electrode **212** of Fig. 2A, while intermediate electrode **414** is similar to intermediate electrode **214** of Fig. 2A. When intermediate electrode **414** is deflected from its initial position toward lateral electrodes **412**, a link rod **456** transfers motion of the intermediate electrode to inner disk **454** of gimbal structure **450**, thereby rotating the disk as further described below.

Direction, in which intermediate electrode **414** is deflected, is determined by voltages applied to lateral electrodes **412a-c**. In general, intermediate electrode **414** can be deflected in any chosen direction by applying an appropriate combination of bias voltages. For example, suppose that the plane orthogonal to substrate **470** and passing through axis AB is a plane of symmetry for lateral electrode **412b**. Then, when lateral electrode **412b** is biased with respect to intermediate electrode **414**, while the other lateral electrodes **412a** and **412c** are not biased, the intermediate electrode is pulled toward electrode **412b** along the projection of axis AB onto substrate **470**. This rotates disk **454** and therefore plate **402** about axis CD. Similarly, when electrodes **412a-c** are biased such that intermediate electrode **414** is pulled along the projection of axis CD, disk **454** and plate **402** rotate about axis AB. One skilled in the art will appreciate that deflection

of intermediate electrode **414** in an arbitrary direction will generally produce rotation of disk **454** and plate **402** about both axis AB and axis CD.

Different fabrication techniques may be used to fabricate devices of the present invention. In one embodiment, a fabrication process similar to that disclosed in the above-referenced U.S. Patent Application No. 10/772,847 may be used. Briefly, the fabrication process begins with a silicon-on-insulator (SOI) wafer and proceeds with a sequence of patterning, etching, and deposition steps known to one skilled in the art. The patterning steps are carried out using lithography. The etching steps are carried out using material-specific etching, e.g., reactive ion etching (RIE) for various silicon layers and fluorine-based etching for various silicon oxide layers. The deposition steps are carried out using, e.g., chemical vapor deposition. Additional description of various fabrication steps may be found in U.S. Patent Nos. 6,201,631, 5,629,790, and 5,501,893, the teachings of which are incorporated herein by reference.

U.S. Patent Application No. 10/772,847 also discloses fabrication of flexible vertical beams that are similar to upright springs in certain embodiments of the present invention (e.g., springs **206** of Fig. 2) in that both structure types extend substantially perpendicular to the plane of the substrate. However, an upright spring protrudes through the corresponding movable plate while a flexible vertical beam is confined to the space between the movable plate and the substrate. In view of this difference, fabrication steps related to the realization of the protrusion feature of upright springs are described in more detail below.

Figs. 5A-F schematically illustrate representative fabrication steps of device **200** according to one embodiment of the invention. More specifically, Figs. 5A, 5C, and 5E show top views of device **200** during those fabrication steps, whereas Figs. 5B, 5D, and 5F show the corresponding cross-sectional side views of the device.

Referring to Figs. 5A-B, in one embodiment, fabrication of device **500** begins with a silicon-on-insulator (SOI) wafer having (i) two silicon layers, i.e., a handle layer **562** and an overlayer **566**, and (ii) a silicon oxide layer **564** located between overlayer **566** and handle layer **562**. Plate **502** is defined in overlayer **566** using reactive etching, which stops at the silicon oxide layer. Openings **208a-b** (see also Fig. 2) are created by etching away the corresponding portions of overlayer **566** and silicon oxide layer **564**. Then a timed etch is applied to handle layer **562** to create wells having a depth

corresponding to the length of future upright springs **206**, by which length the springs extend above plate **202** (see Fig. 2).

Referring to Figs. 5C-D, first, a relatively thick (e.g., 5 μm) silicon oxide layer **568** is deposited over the structure of Figs. 5A-B. Second, layer **568** is patterned and etched to form an opening **580** for link rod **216** connecting plate **202** and intermediate electrode **214**. Then, a thin (e.g., 1 μm) poly-silicon layer **572** is deposited over layer **568**. The part of layer **572** that fills opening **580** creates link rod **216**. Finally, layer **572** is patterned and etched to remove poly-silicon from the wells corresponding to openings **208**.

Referring to Figs. 5E-F, first, a thin (e.g., 0.5 μm) poly-silicon layer **574** is deposited over the structure of Figs. 5C-D. This layer covers all exposed surfaces of that structure including the vertical walls of the wells corresponding to openings **208**. Then, the composite silicon layer comprising layers **572** and **574** is patterned and etched to form intermediate electrode **214**, lateral electrodes **212**, and upright springs **206**. In particular, bridge **230** of upright spring **206** (see Fig. 2B) is formed from the portion of layer **574** located at the bottom of the corresponding well; spring segments **228a-b** of upright spring **206** (see Fig. 2B) are formed from the portion of layer **574** located at one of the vertical walls of the well, and two feet **226a-b** of upright spring **206** are formed from the portion of layer **574** deposited near the top circumference of the well. Note that silicon oxide layer **568** prevents upright springs **206** from making contact with plate **302**.

Further fabrication steps are straightforward and proceed to form support posts **204a-b** and substrate **270** over the structure of Figs. 5E-F (see also Fig. 2). The final structure of device **200** is released by removing (e.g., etching away) all oxide layers. Note that handle (silicon) layer **562** will fully detach from the final structure once silicon oxide layers **564** and **568** are removed. Also note that the views shown in Figs. 5B, 5D, and 5F are inversed (flipped) with respect to the view shown in Fig. 2A.

While this invention has been described with reference to illustrative embodiments, this description is not intended to be construed in a limiting sense. Various modifications of the described embodiments, as well as other embodiments of the invention, which are apparent to persons skilled in the art to which the invention pertains are deemed to lie within the principle and scope of the invention as expressed in the following claims.

Although fabrication of MEMS devices of the invention has been described in the context of using silicon/silicon oxide SOI wafers, other suitable materials, such as germanium-compensated silicon, may similarly be used. The materials may be appropriately doped as known in the art. Various surfaces may be modified, e.g., by metal deposition for enhanced reflectivity and/or electrical conductivity or by ion implantation for enhanced mechanical strength. Differently shaped plates, springs, segments, rods, posts, actuators, electrodes, and/or other device elements/structures may be implemented without departing from the scope and principle of the invention. Springs may have different shapes and sizes, where the term "spring" refers in general to any suitable elastic structure that can recover its original shape after being distorted. Spring segments of an upright spring may or may not be parallel to each other. An opening in a mirror segment (e.g., slot **208** in Fig. 2) may or may not be fully surrounded by said mirror segment. Alternatively, a mirror segment may be shaped such that an upright spring passes outside the perimeter of said mirror segment. The length of a link rod (e.g., link rod 216 in Fig. 2) may be chosen such that the axis of rotation for the corresponding mirror segment is not within the plane of that segment. Various MEMS devices of the invention may be arrayed as necessary and/or apparent to a person skilled in the art.